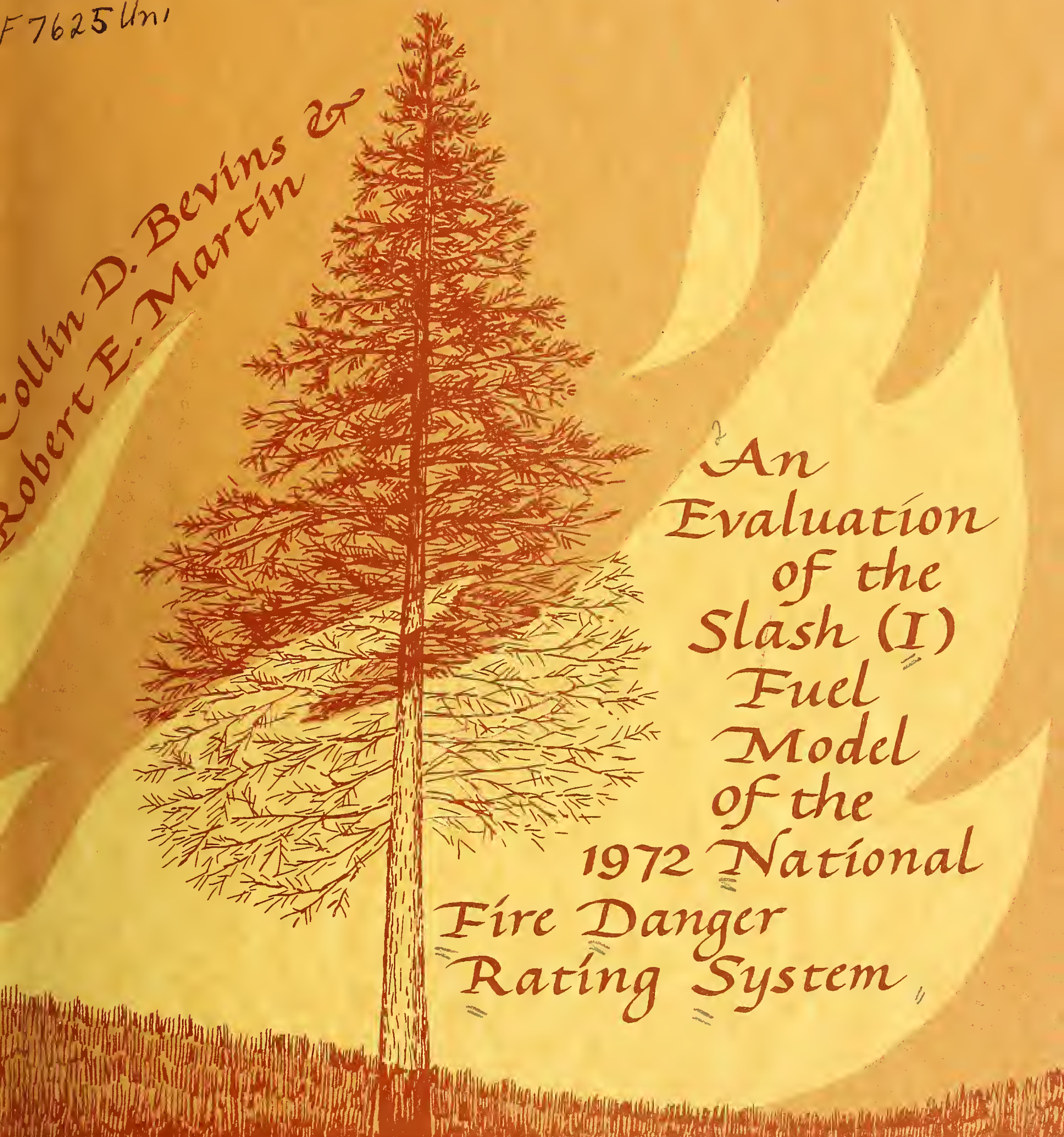
Collin D. Bevins & Robert E. Martin

An Evaluation of the Slash (I) Fuel Model of the 1972 National Fire Danger Rating System



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AN EVALUATION OF THE SLASH (I) FUEL MODEL OF THE 1972 NATIONAL FIRE DANGER RATING SYSTEM

Reference Abstract

Bevins, Collin D., and Robert E. Martin.
1978. An evaluation of the slash (I) fuel model of the 1972 National Fire Danger Rating System. USDA For. Serv. Res. Pap. PNW-247, 17 p. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

The slash (I) fuel model of the 1972 National Fire Danger Rating System was evaluated for homogeneity within the model and for differences from other fuel models. Clearcut slash is different from partial cut slash at the 1-percent level of confidence. Pacific Northwest clearcut slash loads are different from other clearcut slash at the 5-percent level. New fuel models are proposed.

KEYWORDS: Fire danger rating, slash, fire behavior (Forest), fuels (forest fire), models.

RESEARCH SUMMARY

Research Paper PNW-247

1978

The slash (I) fuel model of the 1972 NFDRS was evaluated with respect to the specific fuel parameters in comparison to measured values in the field. Proposals are made for new fuel models. Statistical comparison at the present level indicate two western slash fuel models would be better, one representing clearcut slash, the other partial cut slash. If the 5-percent level of significance is used, separate clearcut slash loads should be used for Pacific Northwest clearcuts and other western clearcuts. The proposed clearcut model has selected load values similar to the slash (I) fuel model, and loads for the partial cut model are only 68 percent of the clearcut model. Packing ratios are higher than in the I model.

Introduction

The National Fire Danger Rating System (NFDRS), implemented in 1972, is a two part system based upon fire occurrence and fire behavior indices. Fire occurrence is a function of the ignition probability and prevalence of ignition sources, but fire behavior depends upon the relative rate of fire spread, energy release, and flame length (Schroeder et al. 1972). The 1972 NFDR System was developed at the Rocky Mountain Forest and Range Experiment Station of the USDA Forest Service, Fort Collins, Colorado, beginning in the spring of 1968. At that time the projected operational target date was set for 1972. The target date was met and a summary publication was made available in February of that year (Deeming et al.1972). A more complete history of the conception and implementation of the NFDRS is given by Deeming and Brown[1] and Deeming and Lancaster (1971).

The fire behavior portion of the NFDRS is based upon a mathematical fire spread and intensity model developed at the Northern Forest Fire Laboratory of the USDA Forest Service, Missoula, Montana (Rothermel 1972). This model requires several inputs for its solution. A number of these inputs are fuel parameters that describe the wildland fuel situation, and as a set are referred to as a fuel model. Nine such fuel models are currently used by the NFDRS to represent all wildland fuel situations in the U.S. In the construction of the NFDRS fuel models, an attempt was made to use modal values of fuel descriptors characterizing the typical fuel complex to be represented. Data, however, on many of the fuel parameters were either scarce or nonexistent, and in many instances selection of the model parameter values was based upon a combination of objective and subjective observations and estimates. Furthermore, the number of models to be used was determined from a consensus of opinion rather than an analysis of fuel type range and variance (Deeming and Brown 1972). These difficulties were unavoidable due to lack of time before the 1972 implementation date.

The NFDRS project has sought more objective and quantitative evaluation of the System's fuel models. The grass fuel model was evaluated first, and a methodology for evaluating fuel models was established (Sneeuwjagt 1974). The objective of the study reported here was to evaluate the activity-created slash (I) model of the NFDRS. The results of the study would be used in development of fuel models for the 1978 version of the NFDRS.

Study Approach

The 1972 NFDRS incorporates a single fuel model to characterize all western conifer clearcut slash fuels. This fuel type is represented by the System's slash (I) fuel model, whose general and specific parameters are shown in table 1. The general parameters have a constant value for all nine fuel models due to either a low natural variability between fuel types, or the fire model's insensitivity to them (Deeming and Brown 1972). The specific parameters vary from one fuel model to the next, and include the fuel load by size class, the fuel bed depth, and the fine fuel's surface-area-to-volume ratio.

Meeting the objective of the study involved addressing the following questions.

(1) Are all clearcut slash fuel situations members of the same statistical population, regardless of activity-type or physiographic location, or do they occur in several distinct populations?

(2) Is the clearcut slash fuel population(s) statistically different from the other eight fuel model populations, particularly the G fuel model which represents natural dead and down fuels under a dense conifer canopy?

[1] Deeming, J. E., and J. K. Brown. 1972. Fuel models of the National Fire Danger Rating System. USDA For. Serv. Rocky Mountain For. and Range Exp. Stn., Fort Collins, Colo. (Unpublished).

Table 1--Values used for parameters in the Slash (I)[1/] Fuel Model of the 1972 National Fire Danger Rating System. General parameters are common to all nine fuel models, whereas specific parameters are set separately for each fuel model

Parameter	Symbol	Value
General parameters		
Low heat of combustion	h	18 603 j/g
Fuel particle density	ρ_p	.513 gm/cm^3
Total mineral content (odw)[2/]	S_T	.055 odw[2/]
Silica-free mineral content	S_e	.020 odw[2/]
10-hour surface area/volume	σ_{10}	3.58 cm^{-1}
100-hour surface area/volume	σ_{100}	0.98 cm^{-1}
Moisture of extinction	M_x	.250 odw[2/]
Specific parameters		
1-hour loading	ω_1	.897 kg/m^2
10-hour loading	ω_{10}	1.121 kg/m^2
100-hour loading	ω_{100}	2.242 kg/m^2
1-hour surface area/volume	σ_1	49.21 cm^{-1}
Fuel bed depth	δ	106.7 cm

[1/]The Slash (I) Fuel Model was designed to represent fuel loads in clearcut conifer areas representing only a midrange fuel load for such areas in the West (Deeming et al. 1972).

[2/]odw = ovendry weight.

(3) Are the current I model specific parameter values representative of or near the mode of actual western conifer slash fuel population(s)?

(4) Are the current NFDRS general parameter values representative of western conifer slash species?

The approach used in the study was to collect all data available from the western National Forests on each parameter to obtain an estimate of the population distribution of that parameter. The means and variances of these distributions were then examined for their uniqueness and certain critical fire values, and representative estimates of parameter values were selected. The selected values were then compared to the NFDRS values. The resulting recommendation was based upon (1) the difference between the selected value and the NFDRS value, and (2) the sensitivity of the Rothermel fire spread and intensity model to this difference.

Sensitivity Analysis

A sensitivity analysis of the Rothermel fire model was made using the NFDRS slash (I) fuel model parameter values as the baseline inputs. The fuel moisture content was set at 0.100 fraction of ovendry weight (odw)[2] for all fuel size

[2]Mineral contents are given as a fraction of ovendry weight (odw). There are no dimensions.

classes, with a moisture of extinction of 0.200 fraction odw. The slope was 50 degrees with a windspeed of 8.0 kilometers per hour.

A standard computer package, FIREMOD (Albini 1976), was used to obtain the baseline output values for the fire behavior variables of rate of spread, fireline intensity, and flame length. Subsequent runs of FIREMOD were made altering a single input parameter's baseline value by plus or minus 10 percent. The sensitivity of the fire model to the 10-percent change in input was expressed as percentage change in the values of each of the three fire variables.

The results, (table 2) show the fire model to be most sensitive to the slash fuel model's low heat of combustion (h), fine fuel load (ω_1), fine fuel surface-to-volume ratio (σ_1), fine fuel moisture content (M_{f_1}), fuel bed depth (δ), and windspeed (U). A change of 10 percent in any of these input parameters results in a proportional change in the fire variable predictions. As noted in a similar analysis by Mission Research Corporation (1975), such sensitivity patterns are expected since the low heat of combustion and windspeed enter into the fire model evaluations as multiplying factors of the reaction intensity and rate of spread. The

Table 2--Sensitivity analysis of the Rothermel Fire Model to NFDRS Slash Fuel Model Parameters. Values in the table are percent changes in the variable resulting from a 10-percent change in the parameter[1/]

Parameter	Rate of spread	Fireline intensity	Flame length
	- - - -	Percent changes	- - - -
Low heat of combustion (h)	100.0	20.0	9.5
Fuel particle density (ρ_p)	1.4	(+)	--
Total mineral content (S_T)	(-)	-1.2	--
Silica-free mineral content (S_e)	-1.9	3.8	--
1-hour loading (ω_1)	5.0	11.7	5.7
10-hour loading (ω_{10})	-2.0	(-)	--
100-hour loading (ω_{100})	-4.3	-2.2	(-)
1-hour surface area/volume (σ_1)	6.5	-2.2	-1.3
10-hour surface area/volume (σ_{10})	(-)	--	--
100-hour surface area/volume (σ_{100})	(+)	1.5	(+)
1-hour moisture content (M_{f_1})	-4.0	-5.0	--
10-hour moisture content ($M_{f_{10}}$)	(-)	(-)	--
100-hour moisture content ($M_{f_{100}}$)	--	--	--
Fuel bed depth (δ)	11.4	10.5	5.1
Moisture of extinction (M_x)	1.0	2.5	1.3
Slope (S)	2.5	2.5	--
Wind (U)	11.5	11.5	10.1

[1/] Minus signs indicate an inverse relationship, plus or minus signs in parenthesis indicate a response less than 1 percent, and dashes indicate no response.

fuel bed depth is used to derive the fuel array's packing ratio, which in turn is used in most of the fire model's intermediate calculations. Since FIREMOD and the NFDRS Spread Components weight input parameters by the surface area contribution of each fuel size class, we would also expect the fine fuel parameters of load, moisture content, and surface-area-to-volume ratio to exert a strong influence on the model's prediction.

Fuel Load Estimates

Data for the analysis of the fuel load parameters for the 1-, 10-, and 100-hour timelag fuel size classes of the I and G fuel models originated from two sources. The first source is data we collected by planar intersect inventories on 31 stands in Region 6 subjected to various stand treatments. The second source is data from Forest Service Regions 1, 3, 5, 6, and 10, solicited from Regional, Forest, and District offices. Only those stand inventories compiled using the planar intersect technique (Brown 1974) were used in the analysis. A total of 235 activity-created fuel inventories and 122 natural dead and down fuel inventories were collected (table 3). Of the activity-created fuel inventories, 144 were in clearcut slash.

The load data were quantitatively analyzed by performing a series of one way analyses of variance (ANOVA) on several data groupings, allowing for a test of the number of distinct fuel load populations.

Certain assumptions inherent in the ANOVA process have to be made to maintain statistical validity. First, it is necessary to assume the collected data constitute a random sample of all western slash areas. This assumption is necessarily false to an unknown degree since this type of data exists in limited amounts in limited areas, but an attempt was made to gather as much of it as possible for the analysis. The data may deviate from randomness because of a tendency for field offices to sample the heavier, more hazardous stands in the protection unit rather than gather a random sample from the entire range of loading situations. The results would give heavier fuel load estimates. Also, fuel load inventory is much more common in Regions 1 and 6 than elsewhere, so more data exist for these areas. The second statistical assumption is that the populations of fuel loads are normally distributed and homogeneous in variance for each fuel type and each size class.

Other assumptions of a nonstatistical nature have to be made to provide a starting point for the ANOVA. We first assumed that the load data can be divided into smaller groups based upon two stratifications--first, the type of activity that created the slash, and second, the physiographic location of the stand. In the first category, four activity-types are initially recognized--clearcutting, precommercial thinning, other partial cutting methods (overstory removal, sanitation cuts, shelterwood cuts, etc.), and natural dead and down fuels (no activity). In the second category, only two physiographic groups are recognized. The first includes all the data from the west side of the Oregon and Washington Cascade crest and the southeastern forests of Alaska where the precipitation is very high and the winters are mild. Data from the coast of northern California could also be part of this group, but none were available in this study. The second assumed physiographic population consists of data from all other areas of the Western United States.

We first conducted an ANOVA between the two physiographic groupings to test for significant differences in means of fuel loads. An ANOVA was then run on the four activity-type groups, comparing (1) thinning data with other partial cut data, (2) thinning plus partial cut data against clearcut data, and finally (3) natural dead and down fuel data versus any of the other treatments. The stepwise procedure was repeated for the fuel load data of each size class of woody fuel to allow for the progressive consolidation

Table 3--Fuel load inventory data sources[1/]

Source	Type of slash fuel inventoried							
	Clearcut	Thinning	Partial cut	Overstory removal	Sanitation	Shelterwood	Select cut	Natural
	Number of inventories							
Region 1								
Northern Forest Fire Laboratory	21							
Clearwater National Forest	9			6	9			4
Regional Office	25	6	4	4	1	5		
St. Regis National Forest, St. Regis Ranger District	1	15		3		2		
Panhandle National Forest								100
Region 2								
Regional Office	11	7	1				4	
Region 3								
Regional Office	12							
Region 5								
Modoc National Forest, Doublehead Ranger District	2	4	3					4
Region 6								
Bevins (1975)	24	5	1					1
Schmidt (1975)	14	3						6
Swanson (1974)	1							7
Regional Office	4	4	4					
Region 10								
Regional Office	20							

[1/]All fuel loadings used were measured by the planar intersect method (Brown 1974).

of smaller, assumed groupings into larger, statistically alike populations, until one or more distinct fuel distributions emerged. When combined, the distinct populations (or population) should cover the entire continuum of the western slash fuel loading and serve as a test of the 1972 NFDRS' implicit assumption that a single fuel model can adequately define all western conifer clearcut fuel situations. In processing the screen this way, we have possibly increased the probability of obtaining a significant difference among fuel groups.

The two assumed physiographic populations were not statistically different at the 1-percent level of significance (tables 4 and 5). They did exhibit considerable differences in 10- and 100-hour fuels but not in the 1-hour fuel. In keeping with the NFDRS aim to use a minimal satisfactory number of fuel models, the analysis was continued, assuming no difference between the two physiographic provinces. More extensive sampling might indicate significant differences between the two populations. Within the activity-type category, the thinning and partial cut populations are also found indistinct from each other at the 1-percent level for all three fuel size classes and were consolidated into a single partial cut data group. This consolidated population is significantly different at the 1-percent level from the clearcut fuel population for the 1- and 100-hour size classes, but not for the 10-hour class. Finally, the natural dead and down fuel loads are distinct from all activity-created fuel loads, except in the 1-hour size class where it is not different from the clearcut population.

From these results, it appears that two distinct slash fuel load

Table 4--Fuel loads and standard deviations of the 1-, 10-, and 100-hour timelag classes of woody fuels for activity slash and natural down and dead fuels

Population	Mean	SD
	- - - - kg/m^2 - - - -	
1-hour fuels		
Clearcut (Pacific Northwest)	0.214	0.116
Other clearcut	.255	.187
All clearcut	.242	.167
Partial cut	.119	.067
Natural	.243	.223
10-hour fuels		
Clearcut (Pacific Northwest)	.632	.429
Other clearcut	.912	.781
All clearcut	.789	.662
Partial cut	.749	.424
Natural	.318	.211
100-hour fuels		
Clearcut (Pacific Northwest)	1.706	.723
Other clearcut	1.417	.794
All clearcut	1.543	.774
Partial cut	1.234	.746
Natural	.638	.397

Table 5--Analysis of variance of fuel loads among various categories of cutting and natural down and dead fuel loadings

Treatments	F(DF)[1]		Significance level (percent)
1-hour fuels			
Thinning vs. partial cut	1.19	(1, 50)	NS[2]
Clearcut vs. partial cut	24.96	(1, 22)	99.5
PNW clearcut vs. other clearcut	.95	(1, 70)	NS
Natural vs. clearcut	.00	(1, 192)	NS
10-hour fuels			
Thinning vs. partial cut	3.17	(1, 90)	90
Clearcut vs. partial cut	.27	(1, 234)	NS
PNW clearcut vs. other clearcut	6.602	(1, 142)	97.5
Natural vs. partial cut	95.16	(1, 212)	99.5
100-hour fuels			
Thinning vs. partial cut	4.51	(1, 90)	90
Clearcut vs. partial cut	9.21	(1, 234)	99
PNW clearcut vs. other clearcut	5.09	(1, 142)	95
Natural vs. partial cut	56.62	(1, 212)	99

[1] F = F ratio, DF = degrees of freedom.

[2] NS = not significant at 90-percent level.

populations exist along the fuel load continuum, both of which are unlike the natural dead and down fuel situation characterized by the G fuel model (see footnote 1). These two slash fuel load populations correspond to clearcut treatments and all partial cut treatments.

Fuel Load Parameters

Values for the load parameters of the two activity-created slash fuel models were selected based upon the NFDRS' "average-bad" philosophy (Deeming and Lancaster 1971). Under this philosophy, each fuel model should be equal to or overestimate most of the fuel load situations it is modeling. That is, instead of using a mean load value where 50 percent of the real world fuel loads are underestimated by the model, a higher value should be chosen that would reduce this underestimation. The critical level chosen, however, should overestimate most of the fuel load situations, yet be located near the mean of its distribution curve. If the selected value lies too far out into the right tail of the curve, it is no longer representative of that population. Under these criteria, fuel load values were selected from the 67 percent of the population's normal distribution curve. This value should represent the entire population while overestimating two-thirds of the actual fuel load situations.

Under the assumption of a normal distribution, the 67-percent frequency level value was derived by:

$$\text{67-percent level} = \bar{\omega} + 0.44\, s_{\omega} \;; \quad (1)$$

where, $\bar{\omega}$ is the fuel size class mean load and s_{ω} is its standard deviation.

Table 6 summarizes the 50-percent critical level (mean), standard deviation, and 67-percent critical level for the three size classes of the clearcut and partial cut load populations.

Table 6--Mean, standard deviation, and selected fuel loading values for 1-, 10-, and 100-hour timelag fuel classes from clearcut, partial cut, and natural down and dead situations

Fuel type	Needles	1-hour			10-hour			100-hour		
	67%	50%	SD	67%	50%	SD	67%	50%	SD	67%
		Kilograms/meter^2								
Clearcut	0.545	0.242	0.167	0.315	0.789	0.662	1.080	1.543	0.774	1.885
Partial cut	.260	.119	.007	.150	.749	.442	.935	1.234	.745	1.560
Natural	--	.243	.223	--	.318	.211	--	.638	.397	--

Needle loading.--Needle loads should be included in the fuel loads for the 1-hour size class since the NFDRS considers "average-bad" conditions. Because many slash units are not treated until after the very flammable "red slash" stage, adding the needle component makes a closer approximation to the potential fire behavior.

The needle loading value was taken from Fahnestock's (1960) ratios of needle weight to 1-hour size class branch wood weight (r) for live crowns of three common timber species as tabulated below.

Species	r values
Lodgepole pine (*Pinus contorta* Dougl.)	1.34
Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)	2.25
Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)	1.59
Average	1.73

The average value for r is 1.73, and needles therefore contribute an extra 173 percent to the 1-hour fuel loads and make up 63.4 percent of the total 1-hour fuel load in partial and clearcut slash.

Fine Fuel Surface Area-to-Volume Ratio

The fine fuel surface area-to-volume ratio (σ_1) is another fuel model specific parameter, and for the slash fuel models, has to be representative of both the needle and woody branch wood components. The range of σ_1 is therefore very large, from 99.8 cm^{-1} for western hemlock needles (Brown 1970a) to 11.8 cm^{-1} for lodgepole pine twigs (Brown and Roussopoulos 1974). Values in table 7 for σ of four common slash species' needles, 1-, 10- and 100-hour fuels were derived from mean particle diameter data by

$$\sigma = 4 / \bar{d}; \qquad (2)$$

where, d is the mean particle diameter in centimeters, and the particles are assumed to be cylindrical in shape with negligible surface area on the ends.

The average for needles of the conifer slash species is 72.8 cm^{-1}, and 18.3 cm^{-1} for the 1-hour branchwood. The needle component receives a weighting factor of 0.634 based upon its mass contribution to the 1-hour size class fuel loading, and the woody component's σ is weighted by 0.366. The resulting weighted surface area-to-volume ratio for the fines, σ_1, is 52.8 cm^{-1}. This value is 7.3 percent greater than the current NFDRS value of 49.2 cm^{-1}. The sensitivity analysis indicates that use of the new value of 52.8 cm^{-1} will increase the rate of spread prediction by only 4.7 percent. Given the wide range of values and

Table 7--Surface area-to-volume ratios for common conifer slash species

Species	Needles (cm^{-1})	1-hour (cm^{-1})	10-hour (cm^{-1})	100-hour (cm^{-1})
Ponderosa pine	57.6[1/]	--	2.96[2/]	0.98[2/]
Lodgepole pine	64.74[1/]	11.8[2/]	3.23[2/]	.89[2/]
Douglas-fir	69.1[1/]	15.4[2/]	3.23[2/]	.98[2/]
Western hemlock	99.8[1/]	27.6[3/]	2.80[3/]	.90[3/]
Average	72.8	18.3	3.06	.94

[1/]Brown (1970a).

[2/]Brown and Roussopoulos (1974).

[3/]Bevins (1978).

the weighting method used, the small difference between the selected and NFDRS values, and the resolution required by the System, we feel that the current NFDRS value of 49.2 cm^{-1} is acceptable and representative of fine slash fuels.

Fuel Bed Depth

An ANOVA of the highest particle intersect fuel bed depth data was performed for the clearcut treatments versus the partial cut types, and the two populations were found to be different at the 1-percent significance level. The highest particle intersect depths were used since they are part of the standard planar intersect inventory method (Brown 1974) and are included in most of the collected inventory data.

Because the vertical distribution of logging slash is not uniform (Brown 1970b, Bevins 1975), use of the highest particle intersect depth tends to overestimate the fuel bed depth and underestimate the bed's bulk density and packing ratio. A more accurate and appropriate depth value is the bulk depth, the depth through which the bulk density of the fuel array is maintained (Frandsen 1974). An empirical relationship has been established between the bulk depth and the highest particle intersect depth based upon duplicate depth measurements taken at the same point using both techniques. A limited number of areas were sampled and may be very weak in representing non-clearcut areas. The data for the relationship were collected from 24 clearcuts, 5 precommercial thinnings, 1 partial cut in a regeneration unit, and a natural dead and down area. The relationship between the two depths is:

$$\text{Bulk Depth (cm)} = 2.26 + 0.52 \text{ Highest Intersect depth (cm)} . \quad (3)$$

The r^2 of the relationship is 0.83. The standard error of the estimate is only 3.51 centimeters, or 18.5 percent. We believe the equation to be both accurate and precise enough to reduce the highest particle intersect depths to bulk depths.

The 67-percent levels of the two fuel type bulk depths were derived using equations (1) and (3). Use of the 67-percent value maintains the convention previously used in the derivation of the fuel load values, raises the fuel bed depths nearer to their optimum levels, and upholds the NFDRS' "average-bad" philosophy. The resulting values are 32 centimeters for clearcut slash, and 15 centimeters for the partial cut slash model (table 8). Both values are significantly lower

Table 8--Highest intersect and bulk depths for partial and clearcut slash

Fuel type	Highest intersect mean	Standard deviation	Estimated bulk depth mean	Bulk depth 67th percentile
	Centimeters			
Clearcut	43.4	26.2	20.3	31.8
Partial cut	22.2	12.3	9.3	14.7

than the current NFDRS bed depth for slash of 106.7 centimeters.

General Parameter Values

Low heat of combustion.--Mean values for the low heats of combustion for five major slash species have an average value of 19 992 joules/gm (table 9), 7.5 percent higher than the current NFDRS value of 18 603 j/g. This produces a 7.5-percent increase in the rate of spread prediction, a 15-percent increase in the fireline intensity, and a 7-percent increase in flame length. Because the low heat of combustion of conifers seldom drops below 18 603 j/g, and because of the fire model's sensitivity to this parameter, it is recommended that it be included as a specific parameter in the two proposed slash models with a value of 20 000 j/g.

Particle density.--The sensitivity analysis indicates that the fuel particle density would have to drop from 0.513 g/cm^3 to 0.330 g/cm^3 or increase to 0.696 g/cm^3 to effect a 5-percent change in the fire model's rate of spread prediction. Due to this low fire model sensitivity and the restricted range of conifer slash wood densities, the current value of 0.513 g/cm^3 is acceptable.

Table 9--Low heat of combustion for five common conifer slash species

Species	Low heat of combustion	Source
	Joules/gm	
Ponderosa pine (*Pinus ponderosa* Laws.)	20 930	Brown 1972
Lodgepole pine (*Pinus contorta* Dougl.)	18 921[1/]	Corder 1973
Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)	20 386	Brown 1972
Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)	18 460[1/]	Corder 1973
Western redcedar (*Thuja plicata Donn*)	21 265[1/]	Corder 1973
Average	19 992	

[1/]Adjusted from high to low value by subtracting 5 434 joules/gm.

Total mineral content.--Similarly, the total mineral content would have to change by more than an order of magnitude to effect a 5-percent change in the fire model behavior predictions. The current value of 0.055 fraction odw is close to Philpot's (1970) values for ponderosa pine needles (0.039) and white pine needles (0.033).

Silica-free mineral content.--Philpot (1970) found the silica-free mineral content (S_e) of ponderosa pine and Douglas-fir bolewood to be equal to the total mineral content of these species; .002 and .001 fraction odw, respectively. The needles of ponderosa pine and white pine, however, have an S_e of .015 and .025, 10 times higher than the bolewood. Because the needle component contributes 78.6 percent of the surface area of the clearcut model and 72.8 percent of the partial cut model, the current NFDRS S_e value of .020 fraction odw appears appropriate for these two fuel types.

Ten- and 100-hour size class surface area-to-volume ratios.--The average values for ponderosa pine, lodgepole pine, Douglas-fir, and western hemlock σ_{10} and σ_{100} are given in table 6. The average σ_{10} of 3.06 cm^{-1} is 15 percent lower than the general parameter value of 3.58 cm^{-1}. This difference will have a negligible effect on the fire model's predictions. Similarly, the average σ_{100} from table 6 of 0.94 cm^{-1} is only a 4-percent decrease from the NFDRS value of 0.98 cm^{-1}, and would have almost no effect on the fire model's predictions. It appears, then, that the current general parameter values used by the NFDR System for σ_{10} and σ_{100} are representative of slash fuel species.

Moisture of extinction.--While the NFDRS considers the moisture of extinction (M_x) to be a general parameter, it appears in fact not to be a constant parameter attributable to a fuel type, but rather a variable dependent upon the fuel array properties. The M_x values that give good agreement between predicted and observed fire spread behavior on 16 experimental slash fires have been found to be positively correlated with the fuel array's characteristic load ($\tilde{\omega}_n$) ($r = .755$) and packing ratio (β) ($r = .480$), and inversely correlated with its characteristic surface area-to-volume ratio ($\tilde{\sigma}$)($r = -.876$). The M_x values ranged from 0.10 to .50 fraction odw. The relationship is expressed by the regression equation

$$M_x = 0.359+0.956\,\beta+0.021\,\tilde{\omega}_n-0.0049\,\tilde{\sigma}\ ; \quad (4)$$

where, M_x is the moisture of extinction value (fraction odw), β is the packing ratio (dimensionless), $\tilde{\omega}_n$ is the characteristic fuel load (kg/m^2), and $\tilde{\sigma}$ is the characteristic surface area-to-volume ratio (cm^{-1}). The equation has an R^2 of 0.80 and a standard error of estimate of 0.08. Equation 4 yields an M_x value of 0.182 for the clearcut model and 0.203 for the partial cut model. Use of the new M_x values would reduce spread predictions by 2 to 3 percent. Given the standard error of the regression at 0.08, we do not feel sufficient evidence exists to change the current M_x value of 0.25 fraction odw.

Fuel Model Performance

The performance of the clearcut and partial cut models were compared with that of the slash (I) model. The FIREMOD subroutines library was again employed using parameter values listed in table 10 as inputs for the three models.

Model performance was evaluated at four levels of fire danger. The low, moderate, high, and extreme fire dangers correspond to the 10, 50, 80 and 98th percentile worst fire weather days. The Plains, Montana AFFIRMS station was used to determine the percentile fuel moisture values. The station has 2,067 days of weather data between June 1 and September 1 over a 22-year period. The moisture contents (percents) at each danger level are given on the bottom of the next page.

Table 10--Suggested values for clearcut and partial cut slash fuel model parameters, as indicated by our analyses in comparison with the NFDRS Slash (I) Fuel Model[1/]

Fuel model	Fuel load (kg/m^2)			Fuel bed depth (cm)	σ_1 (cm^{-1})	M_x (fraction)
	1	10	100			
Clearcut	0.860	1.080	1.885	32.0	49.2	0.22
Partial cut	.410	.935	1.560	15.0	49.2	.24
Slash (I)	.897	1.121	2.242	106.7	49.2	.250

Fuel model	Packing ratio (dimensionless)	Optimum packing ratio	Optimum bed depth (cm)	Weighted average $\tilde{\sigma}$ (cm^{-1})	Weighted average $\tilde{\omega}_n$ (kg/m^2)
Clearcut	0.02330	0.00911	81.8	44.55	0.910
Partial cut	.03775	.00965	61.0	41.48	.532
Slash (I)	.00779	.00929	89.4	43.47	.948

Fuel model	h (j/g)	ρ_p (g/cm^3)	S_T (fraction)	S_e (fraction)	σ_{10} (cm^{-1})	σ_{100} (cm^{-1})
Clearcut	20 000	0.513	0.055	0.020	3.58	0.98
Partial cut	20 000	.513	.055	.020	3.58	.98
Slash (I)	18 603	.513	.055	.020	3.58	.98

[1/] σ_1 = 1-hour surface area/volume

M_x = moisture of extinction

$\tilde{\omega}_n$ = weighted average net fuel load

h = low heat of combustion

ρ_p = fuel particle density

S_T = total mineral content

S_e = silica-free mineral content

σ_{10} = 10-hour surface area/volume

σ_{100} = 100-hour surface area/volume

$\tilde{\sigma}$ = weighted average surface area/volume

(Tabulation from previous page.)

Danger level	Percentile	1-hour moisture	10-hour moisture	100-hour moisture
Low	10	13	18	16
Moderate	50	7	9	12
High	80	5	6	9
Extreme	98	3	2	6

Table 11 summarizes the predictions of fire spread for the three models under the influence of a 268.2-meter-per-minute (10.0-mile-per-hour) windspeed at midflame height and no terrain slope. While the three models produce distinctly different spread predictions, the clearcut and partial cut model values are much less than those of the slash (I) model. Clearcut model predictions are about one-fourth, and partial cut values one-sixteenth those of the slash (I) model's. This is primarily a result of the higher fuel array packing ratios for the former two models.

Discussion

The NFDRS is a danger rating system using normalized spread (SC) and energy release components (ERC) (Deeming et al. 1972). Each fuel model prediction is normalized against the highest spread rate of the flashiest fuel (grass) and the greatest intensity of the most intense fuel (chaparral). As noted by Rothermel,[3] such a normalization procedure greatly reduces the system's sensitivity to changes in fire danger in slow spreading or low intensity fuels. In the slash (I) model, for example, potential spread rate must increase by more than 2 meters per minute to increase the SC by one unit (see footnote 3). Since the partial cut and clearcut models produce spread rates significantly lower than the I model, their use would only decrease the sensitivity of the models.

Two solutions to the problem are possible. The first is to adjust each model so its spread and energy release values under extreme danger conditions approach those of the grass and chaparral models, respectively. The cause of the low spread rates in the clearcut and partial

[3]Rothermel, R. C. 1974. Evaluating the National Fire Danger Rating System fire behavior indices. NFDRS Tech. Advis. Comm., meet. Nov. 13-14, 1974. Boise, Idaho. Northern For. Fire Lab., Drawer G, Missoula, Mont. 49 p.

Table 11--Rate of spread (ROS) performance of fuel models for various fire danger levels and as a ratio to rate of spread under extreme fire danger conditions

Model	Packing ratio	Low danger		Moderate danger		High danger		Extreme danger	
		ROS m/min	Low/extreme	ROS m/min	Moderate/extreme	ROS m/min	High/extreme	ROS m/min	Extreme/extreme
Slash (I)	Net	14.20	0.499	19.42	0.682	22.53	0.791	28.47	1.00
Clearcut	Net[1/]	3.46	.498	4.73	.682	5.49	.791	6.94	1.00
	Adjusted[2/]	8.72	.497	11.93	.680	13.84	.790	17.50	1.00
	Weighted[3/]	21.19	.498	28.98	.681	33.64	.791	42.53	1.00
Partial cut	Net	.87	.488	1.21	.677	1.40	.785	1.79	1.00
	Adjusted	2.96	.488	4.11	.678	4.77	.785	6.07	1.00
	Weighted	9.36	.488	13.00	.678	15.05	.785	19.18	1.00

[1/]Net $\beta = (\omega_1 + \omega_{10} + \omega_{100})/\delta\rho_p$

[2/]Adjusted $\beta = (\omega_1 + \omega_{10})/\delta\rho_p$

[3/]Weighted $\beta = \tilde{\omega}_n/\delta\rho_p$

cut models are their high packing ratios. As noted in the sensitivity analysis section, the fire model is quite sensitive to changes in this parameter.

The fire model was developed using uniform fuel beds of excelsior, 0.635-cm sticks, or 1.27-cm sticks. The determination of the fuel array packing ratio for such uniform beds is straightforward;

$$\beta = \omega/\delta\ \rho_p; \qquad (5)$$

where, β is the packing ratio (dimensionless), ω is the fuel bed load, δ is the bed depth, and ρ_p is the fuel particle density. When applied to wildland fuels, the determination is not so straightforward. In such cases, the generally used and accepted formula is

$$\beta = \omega_n / \delta\ \rho_p; \qquad (6)$$

where, ω_n is the 'net' fuel load, defined as the load of those fuels with a diameter less than 7.7 cm. This cut-off point is an artifact of the fuel sampling technique (Brown 1974) which divides dead and down fuels into 0- to .63-, .64- to 2.5-, 2.5- to 7.6-, and 7.7- + cm classes.

This presents the possibility of increasing the spread predictions of the clearcut and partial cut models by calculating the packing ratio using other cut-off points. It is important to note that the NFDRS is not concerned with actual spread rate predictions on a real-time basis but rather with relative fire danger rating. Table 11 contains clearcut and partial cut model spread predictions when the packing ratio is determined from only those fuels less than 2.54-cm diameter. The use of such 'adjusted packing ratio' values increases the two models' predictions closer to those of the slash (I) model. This does not alleviate the sensitivity problem, however, since the spread rates are still much less than the spread rate normalizing factor (210.6 m/min).

Another approach was to use the weighted 'characteristic' fuel load $\tilde{\omega}_n$ to determine the packing ratio. The weighted load is the load value used by the fire model to derive reaction intensity (Rothermel 1972) and spread rate. The contribution of each fuel size class load to the characteristic load is weighted by its surface area contribution to the array's total surface area. The use of the weighted characteristic fuel load increases the two models' predictions closer to that of the normalizing factor, making them more responsive to changes in fire danger. Interestingly, the clearcut model's predictions become about 50 percent higher and the partial cut model's predictions 33 percent lower than those of the slash fuel model.

It appears the use of the weighted characteristic fuel load in determining the packing ratio will increase the clearcut and partial cut models' sensitivity to changes in fire danger levels when the danger indices are normalized against high grass fuel spread rates. The two models will also yield danger values distinct from each other, with partial cut indices approximately half those of the clearcut model under similar danger conditions.

The second possible solution to the sensitivity problem suggested by Rothermel (see footnote 3) is to normalize the SC and ERC for each fuel model against its own maximum value under extreme danger conditions. This has the advantage of making the system equally responsive for each fuel model.

Should this approach be taken, the partial cut model should not be included in the 1977 version of the NFDRS. Table 11 demonstrates that if the low, moderate, and high danger spread rates are normalized against the extreme spread rate, all three models produce the same danger index at each level. For example, at low fire danger, the clearcut model spread is 0.498 that of its extreme spread rate. The partial cut model proportion is nearly identical at 0.488.

Conclusions and Summary

An evaluation of slash fuel load data indicates the existence of two statistically different fuel populations at the 1-percent level of significance. One population is associated with clearcut activities and the other with partial cut treatments. Both derived slash fuel populations are statistically different from the most similar non-slash fuel model currently used by the NFDRS, the Dense Conifer (G) model. If the level of significance were dropped to 5 percent, separate clearcut loads should be used for Pacific Northwest clearcuts and other clearcut slash.

The selected load values for the proposed clearcut model are very similar to that of the NFDRS slash (I) model for western conifer clearcuts. The partial cut model's total load is, however, only 68 percent that of the I model's (table 10), and thus represents the lower end of the load continuum. Both proposed fuel models have a much more compacted fuel bed than does the slash (I) model. The increase in packing ratio results in an approximately proportional decrease in the fire model's spread rate predictions. This will further decrease the NFDR System's sensitivity to changes in fire danger for the two new models.

To overcome this difficulty, two alternative recommendations are proposed. The first, as suggested by Rothermel (see footnote 3), is to normalize the SC and ERC against their respective maximum values for each individual fuel model rather than against the grass (A) and chaparral (B) models. This will make every model equally responsive to changes in fire danger relative to its inherent burning properties. Under this recommendation, the proposed partial cut model should not be included in the NFDRS as it will produce danger indices similar to those of the clearcut model.

The alternative recommendation is to increase fuel model spread rate predictions by using the weighted characteristic fuel load to determine the bed's packing ratio. With spread rates more nearly equal to the normalizing factor under extreme burning conditions, the indices of the two proposed models will be more responsive to changes in fire danger. Under this recommendation, both models should be included in the NFDRS as they will produce danger indices distinct from each other. The use of the weighted characteristic load in determining packing ratios for the two models has the same effect as increasing the clearcut model's depth from 32.0 to 134.6 cm, and the partial cut depth from 15.0 to 81.9 cm.

The fine fuels' surface area-to-volume ratio is a difficult parameter for which to derive a value since it must represent both needles and small branch wood. The range of values for this size class is therefore much greater than that of any other class. The influence of the more finely sized fuel particles on fire spread is a well known phenomenon. Because this parameter exerts a fair amount of control over the fire model's spread rate predictions, the creation of a separate fuel size class for particles with surface area-to-volume ratios of greater than 50.0 cm^{-1} (i.e., needles) merits consideration. In the absence of such a fourth size class, a σ_1 was chosen using appropriate weighting methods. The selected fine fuel surface area-to-volume ratio was found to be nonsignificantly different from the current NFDRS value of 49.2 cm^{-1}.

The only change recommended in the NFDRS general parameters is the inclusion of the low heat of combustion as a specific parameter in the newly proposed slash fuel models. Coniferous wood consistently has a low heat of combustion higher than the current value of 18 603 j/g, and this should be reflected in the parameter.

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The slash (I) fuel model of the 1972 National Fire Danger Rating System was evaluated for homogeneity within the model and for differences from other fuel models. Clearcut slash is different from partial cut slash at the 1-percent level of confidence. Pacific Northwest clearcut slash loads are different from other clearcut slash at the 5-percent level. New fuel models are proposed.

KEYWORDS: Fire danger rating, slash, fire behavior (Forest), fuels (forest fire), models.

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